SCIENCE PROGRAM FOR AN IMAGING RADAR RECEIVING STATION IN ALASKA

Report of the Science Working Group

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Front and Back Covers: Color-Classified Seasat SAR Images of a Marginal Ice Zone in the Arctic Ocean off Banks Island.

These images, taken three days apart, have been quantitatively classified using an image texture and spatial pattern analysis technique. Each image is a combination of the color-classified image and the original image, with the following separable classes: red, multiyear ice; black, new or grease ice; yellow, young or pancake ice; and blue, ocean. Algorithms using similar techniques designed to automatically extract sea-ice types and, ultimately, ice-velocity information from SAR imagery require further development to maximize the utility of SAR imagery from future missions. Analysis of these images was performed by JPL staff using Image Processing Laboratory software (front cover: Rev. 1382, October 1, 1978; back cover: Rev. 1425, October 4, 1978).

N

0   20 km

Shallow-water bathymetry patterns are detailed in this Seasat SAR image of the Kuskokwim River, which empties into the Bering Sea, flowing through deep channels separated by near-surface sand bars; Rev. 232, July 13, 1978.

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Foreword

To evaluate the scientific benefits of establishing a station in Alaska to receive radar imagery data from the European Space Agency's Remote Sensing Satellite, ERS-1, NASA formed a science working group consisting of the following members: Gunter Weller, Chairman, University of Alaska; Frank Carsey, Jet Propulsion Laboratory; D. A. Rothrock, University of Washington; and W. F. Weeks, U.S. Army Cold Regions Research and Engineering Laboratory.

Abstract

There would be broad scientific benefit in establishing in Alaska an imaging radar receiving station that would collect data from the European Space Agency's Remote Sensing Satellite, ERS-1; this station would acquire imagery of the ice cover from the American territorial waters of the Beaufort, Chukchi, and Bering Seas; this station, in conjunction with similar stations proposed for Kiruna, Sweden, and Prince Albert, Canada, would provide synoptic coverage of nearly the entire Arctic. The value of such coverage to aspects of oceanography, geology, glaciology, and botany is considered.

Executive Summary

The complex interactions of sea ice with the air and sea significantly influence weather, climate, ocean dynamics, and regional human activities. The observation of sea ice by traditional means is extremely difficult because of the immense scale of the area, its formidable remoteness, and, for in situ observers, the considerable hazard. For these reasons, satellite observations are increasingly relied upon for essential data. The satellite instruments historically most profitable for ice-data acquisition are passive microwave radiometers, now scheduled for operation throughout most of the decade, and imaging radars, especially synthetic-aperture radar, or SAR, scheduled to fly intermittently on Shuttle missions and continuously on the European Space Agency's Remote Sensing Satellite, ERS-1, to be launched in 1988, and the proposed Canadian/United States RADARSAT to be launched about 1990. The Shuttle missions are useful for scientific technique and instrument development, but geophysical studies of sea ice call for uninterrupted data over several years from a free-flying satellite such as ERS-1. It has been suggested that NASA implement a receiving station in Alaska to take full advantage of the SAR carried on ERS-1. Many scientific opportunities are presented with such a station, principally in sea-ice science, but also in oceanography, geology, glaciology, and botany.

The effects of sea ice on the air and sea include an enormous increase in surface albedo, insulation of the warm sea from the cold air, increase in stratus cloud cover, equatorward advection of the latent-heat deficit, alteration of the ocean's mixed-layer stability and surface stress, removal of surface-water carbon dioxide, and the impedance of such human operations as off-shore drilling and navigation. Quantitative evaluation of these processes requires sea-ice measurements that focus on describing the nature of the ice cover and its motion and deformation field. The nature of the ice cover includes its thickness, surface condition, snow cover, floe size and shape, and areal extent.

Scientific investigations that would be enhanced by a SAR receiving station in Alaska are specific to the particular regions within the station's range of satellite reception. These regions and their key features are: the central Beaufort Sea gyre — response of ice to large-scale driving mechanisms; the Beaufort and Chukchi Seas' continental shelves — geophysics of ice/shore interactions; the Bering Strait — ice flow through a narrow strait; the Bering Sea shelf and margin — shallow-water, air/sea/ice interactions in divergent conditions; the entire Arctic — global ice and climatic relationships. Geologic issues of these regions include hydrocarbon exploration studies, river and delta geomorphological dynamics, and shallow-water bathymetry processes. Glaciologic studies include velocity and extent measurements and some descriptions of structure. Vegetation studies include the seasonal

cycle of tundra in the permafrost zones of the North Slope and forestry surveys. Oceanography in these regions concerns both the open seas and the ice margins, with emphasis on the generation and propagation of surface and internal waves, meso-scale surface circulation, and biological productivity.

To pursue these areas of interest in the American and international waters off Alaska and in Alaska itself, it is recommended that NASA establish and operate a SAR receiving station in Alaska. To be effective, about 9 min of data per day should be obtained from the European ERS-1 satellite; negotiations should continue with the European and other space agencies, such as those of Canada and Japan, that are considering SAR deployment. The level of research in the efficient extraction of ice types and floe velocities from SAR images should be increased. The SAR processing system should include a near-real-time capability of about 1 min of data per day to support in situ sea-ice and oceanography experiments, to monitor such critical events as forest and tundra fires, floods, and volcanoes on glaciated mountains, and to define the opportunities and problems in the operational use of SAR images.

All the benefits of SAR-image reception outlined here can be secured with great economy through establishment of an Alaskan station that takes full advantage of the data gathered by a satellite flown by a foreign agency.

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I. Introduction

Sea ice, a rough, uneven, fragmented, shifting cover formed by the freezing of seawater, blankets the oceans, bays, and seas of high-latitude regions, and has a pronounced effect on the net radiation and air/sea exchanges and therefore on the geophysical environment of such areas. Satellite-borne remote sensing has made major contributions to our knowledge of the sea-ice cover of the polar oceans, and at present its use has become operational for both polar regions (Carsey and Zwally, 1983). However, the systems that are currently operational have, by their nature, a number of significant limitations. To be specific, the high-resolution systems that operate in the infrared (IR) and visual bands are limited by clouds and by clouds and darkness, respectively. These are major limitations because the important region near the ice edge is particularly cloudy and the amount of daylight available during the polar winter is at best limited. The operational systems that are not subject to such environmental restrictions are the passive microwave sensors. Although these systems contribute valuable information on ice-edge locations and ice type, they have a coarse resolution, are not capable of discriminating many important ice features, and are not useful in ice-dynamics research.

The sensor with the greatest potential for sea-ice observations is imaging radar, especially synthetic-aperture radar (SAR). A SAR image is a "snapshot" in which features are bright to the extent that they are strong scatterers of the microwave energy emitted by the SAR system (Figure 1). Sea-ice features are characterized by a wide range of scattering coefficients so that there is usually good contrast between old ice, which has survived at least one summer season, first-year ice, which has not been through a summer, new ice, which is less than 10 cm thick, ridges or pileups of ice, and open water (Figure 2). When combining the sensitivity of SAR to variations in ice-surface scattering with its normally fine spatial resolution (10 to 100 m), the discrimination of ice types in a given image is possible as is the tracking of many small ice features in sequential images (Figures 2 and 3). Thus, SAR is a good tool for investigating both the nature of the ice types in the ice cover and the movement and deformation of the cover.
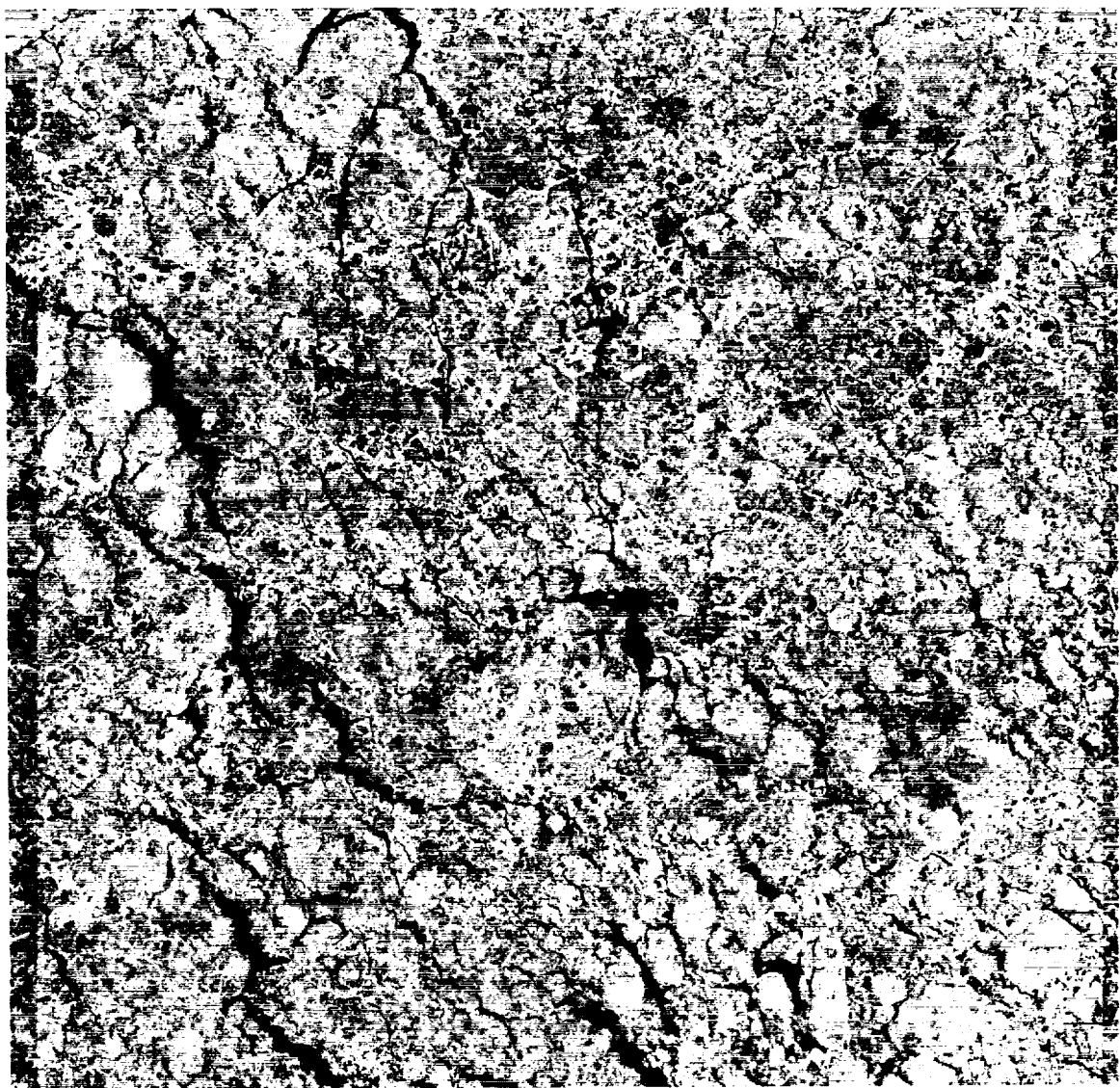
N

0   20 km

Figure 1. Seasat SAR image of pack ice in the Beaufort Sea showing floes crossed by bright ridges and separated by dark leads; Rev. 1382, October 1, 1978.

N

0   20 km
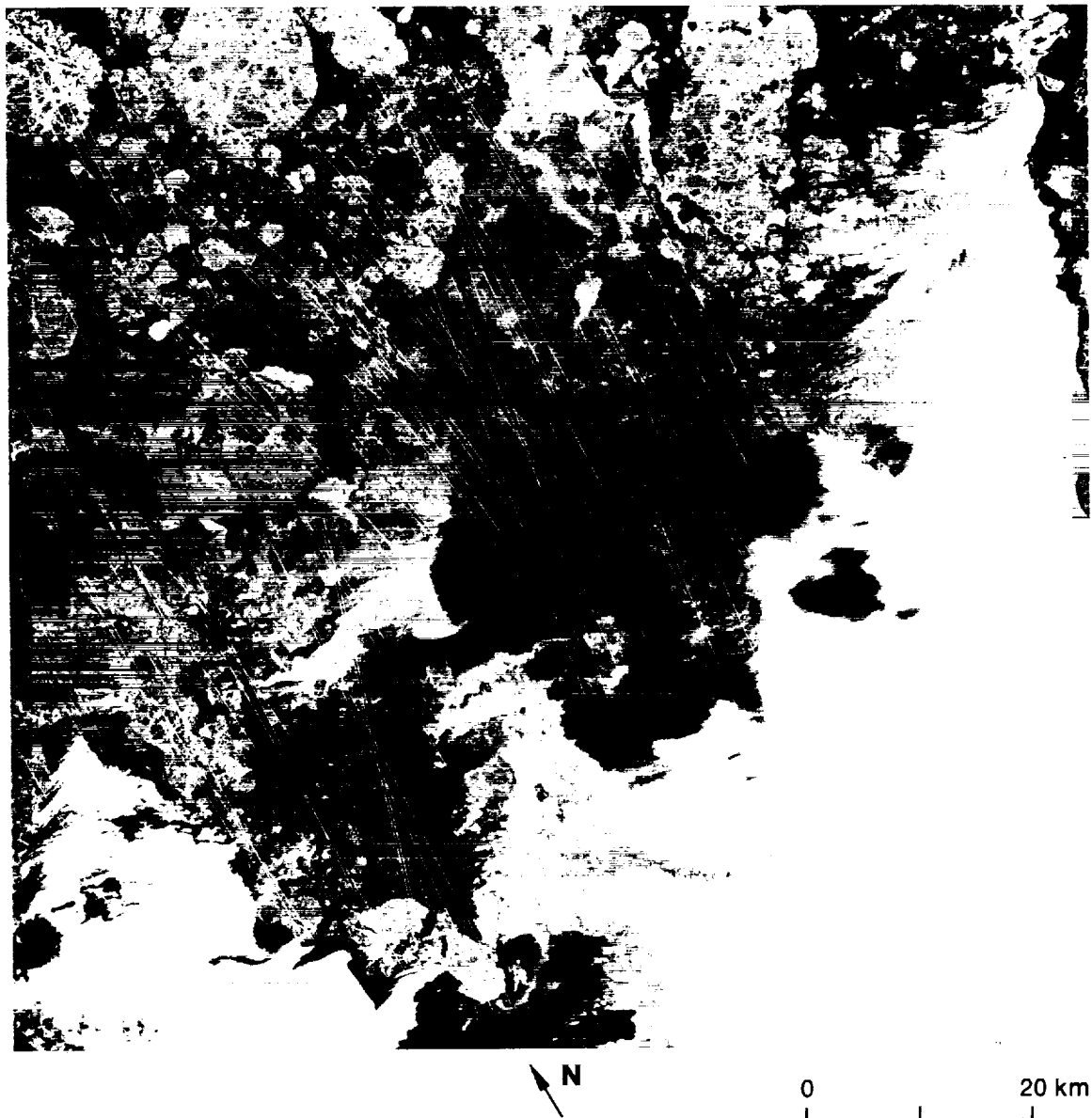
Figure 2. Seasat SAR image of the marginal ice zone off Banks Island (upper right) showing floes, grease ice (dark areas), and open water (bright areas). The image has been digitally processed and registered to an earth-based coordinate system with an accuracy of ± 200 m. The overlain vectors, derived by JPL staff and Image Processing Laboratory software, track commonly identified floes from this image to another image (not shown) and measure the relative floe velocity over a 3-day period; Rev. 1382, October 1, 1978.

(a)

(b)

N
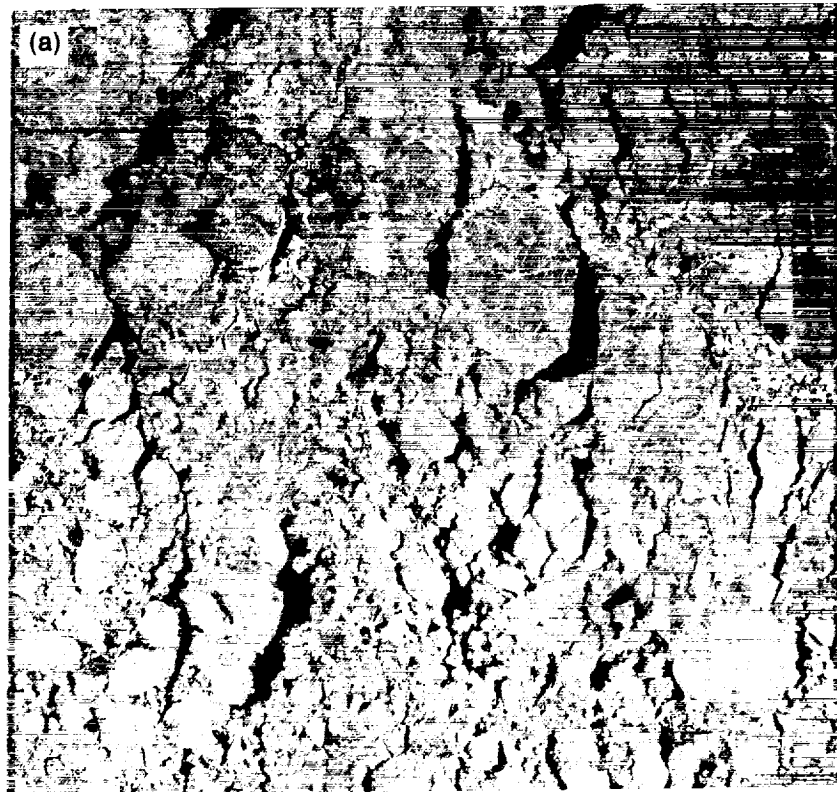
0   20 km
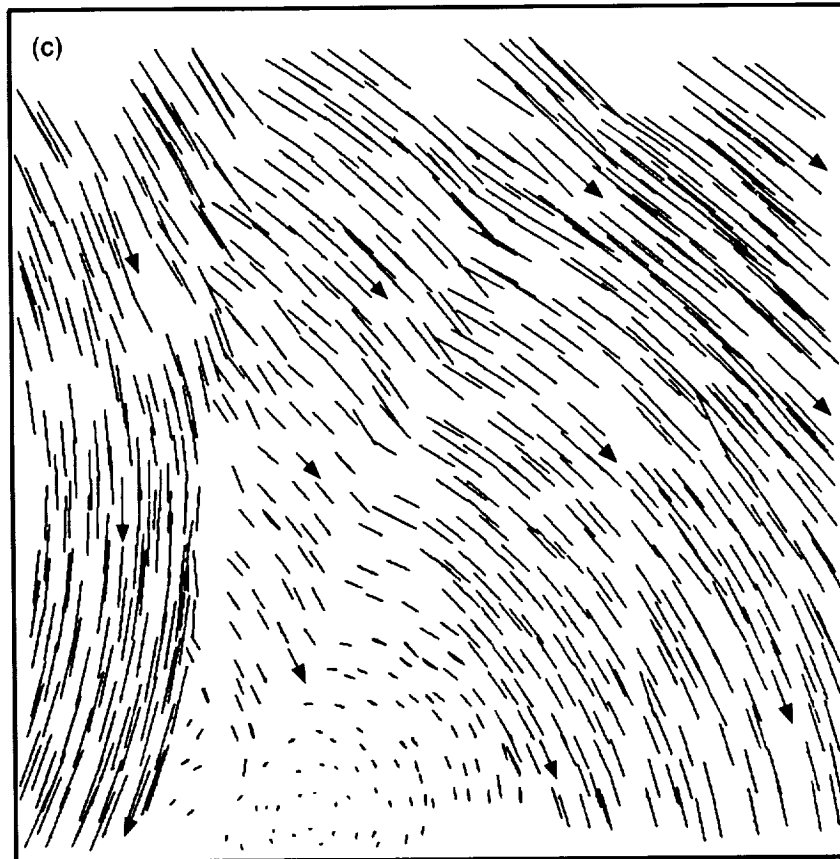
Figure 3. Seasat SAR images of central pack ice in the Beaufort Sea taken 3 days apart: (a) Rev. 1439, October 5, 1978; (b) Rev. 1482, October 8, 1978; (c) relative velocity vectors resulting from tracking over 750 common floes in (a) and (b) (Thorndike and Rothrock, 1983). The images have been digitally processed and registered to an earth-based coordinate system with a location accuracy of ±200 m. The vectors show the complexity of motion in an ice field that is the consequence of air stress, ocean surface tilt, water stress, and force transmitted through the ice. The first two stresses are thought to be essentially constant over the 100-km dimension of an image, while the remaining two stresses are known to have spatial variability but unknown form. The translation vectors were derived by University of Washington scientists working with JPL staff and Image Processing Laboratory software.

A factor in spaceborne SAR implementation is the associated data flow rate; it is so high that data cannot be stored readily on a satellite for later playback. This simply means that reception of SAR data must be in real time, and depends on a line of sight between the satellite and the receiving station. The reception of images of sea ice within United States territorial waters, then, would clearly require a station site in Alaska (Figures 4 and 5). In addition, it is known that three satellites currently under development would carry SAR systems in a polar orbit. These are the European Space Agency's Remote Sensing Satellite, ERS-1, to be launched in 1988; a Japanese radar satellite, to be launched after 1988; and the joint Canadian/ United States RADARSAT, to be launched around 1990 (see Appendix A). Hence, the scientific benefits of establishing an Alaskan receiving station to collect such SAR data from these satellite missions should be evaluated.
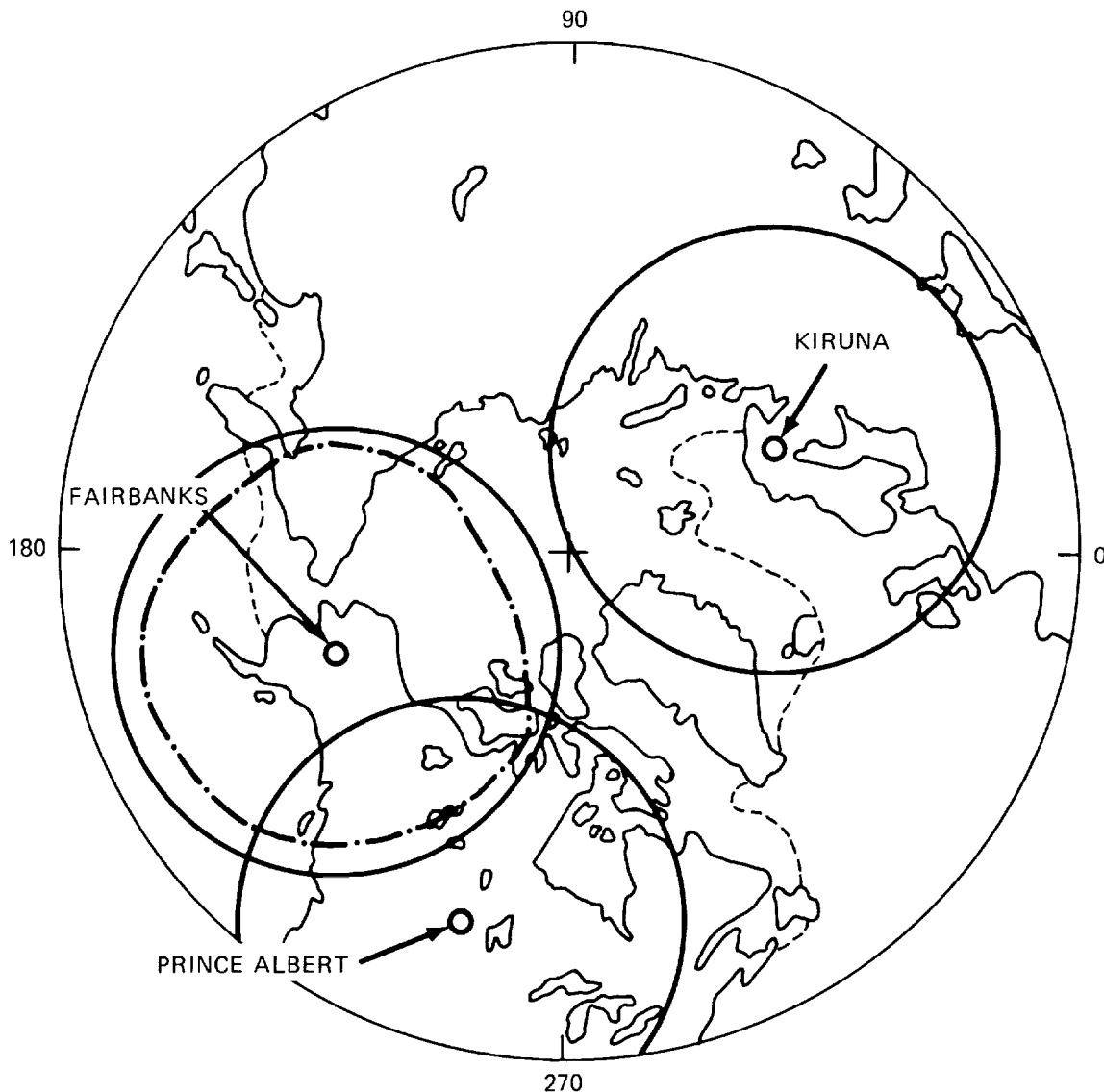
Figure 4. Approximate composite coverage (5-deg horizon) of stations proposed for the reception of SAR data from ERS-1 in the Arctic region. Coverages for two possible station sites near Fairbanks, Alaska, are indicated by a heavy line (the University of Alaska site) and a dot-and-dash line (the Gilmore Creek site). Dashed lines indicate the maximum sea-ice extent.

80°

NORTH LATITUDE

70°

60°

50°

40°

150°

270°

FAIRBANKS

180°

240°

210°

EAST LONGITUDE
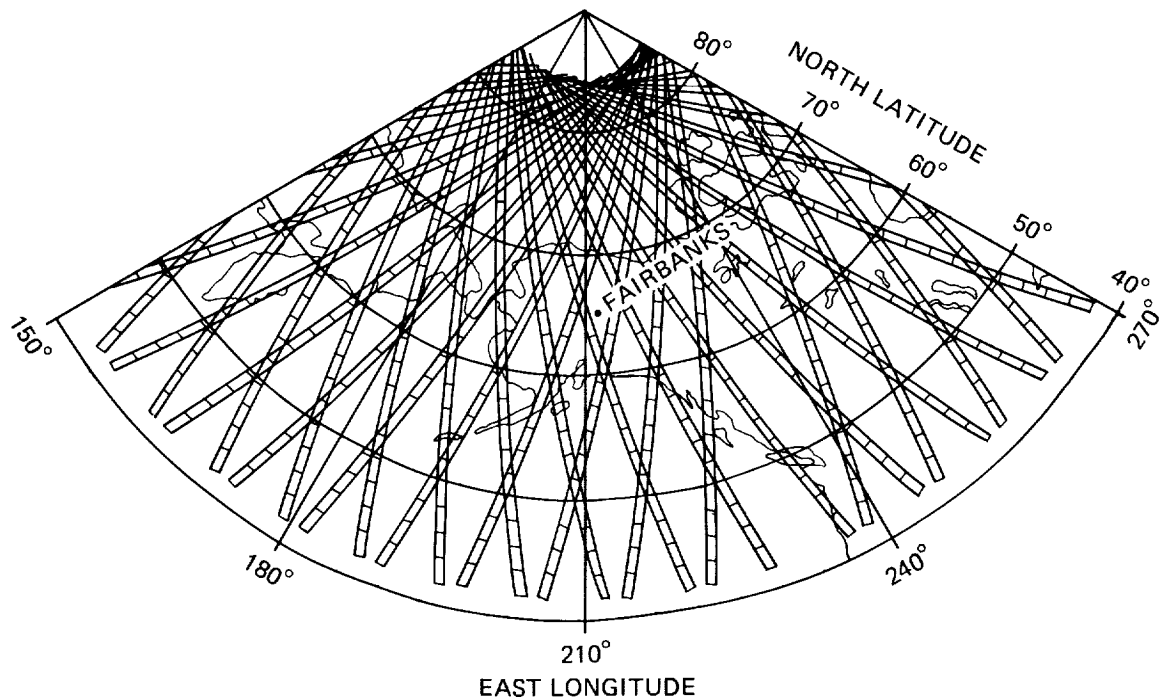
Figure 5. Projected ERS-1 SAR coverage over a 3-day period.

This document briefly discusses the capabilities of SAR in observing sea ice and describes several science programs in the studies of sea ice, oceanography, geology, glaciology, and botany that could be implemented if an Alaskan SAR receiving station were established. Solutions to such operational problems as navigation and oil exploration in ice-covered seas would also be aided by SAR data. The requirements that should be placed upon both the satellite and the receiving station are considered.

II. The Geophysical Role of Sea Ice

Sea ice participates in the air/sea system in a variety of ways, and it is helpful to review these before discussing specific sea-ice science problems (see also Untersteiner, 1961). It is possible with existing data to describe the seasonal cycle of the oceanic ice cover in general terms, and to indicate several processes that are not quantitatively understood even though they are believed to be quite important.

During fall, cooling at the sea surface causes the formation of ice crystals in the form of millimeter-size particles called "frazil ice." These crystals are suspended and mixed by wind-driven turbulence in the upper few meters of the water column. When the turbulence subsides, these crystals float to the surface where they form a fine-grained compact of roughly equidimensional ice crystals called "grease ice." Within 1 to 2 days, these crystals freeze together into a solid cover a few centimeters to a few decimeters thick; this cover then increases in thickness throughout the cold season by bottom surface growth, accumulating up to a 2-m total thickness by the end of the first freezing season. Because the ice produced is relatively fresh, the sea under the growing ice has, effectively, cold dense brine added to it (Weeks and Ackley, 1982). In the Arctic Ocean, about half the ice cover will survive the subsequent summer melt period, and this old ice will grow typically to a mean thickness of 3 to 5 m.

Winds and currents deform and move the ice. Sea ice generally moves in the direction of the geostrophic wind and at about 2% of its speed, or up to 30 cm/s -- an appreciable speed. Deformation occurs when the divergent and shearing motion field pushes ice into pileups called "ridges" up to 50 m thick and produces areas of open water, usually randomly linear, called "leads." Ice advection commonly occurs either as a gyre motion, such as that in the Beaufort and Weddell Seas, or as a net equatorward drift of the ice, as that in the Bering, East Greenland, and Ross Seas. The exact nature of the deformation, or rheology, of the ice in the various situations of shear and divergence is not well understood, largely because the velocity compo-

nent of interest is discontinuous and not readily amenable to traditional mathematical treatment. Although a net equatorward advection of ice is known to commonly occur, the total magnitude and seasonal cycle of this transfer is not well known. This process is an important component of the global poleward transport of heat.

The large area and high albedo of sea ice affect the heat budgets of the ocean and the atmosphere, and thereby influence the polar climate. In the winter season of each hemisphere, 17 to 20 million km^2 undergo an albedo change of 0.1 to 0.2 for open water to about 0.7 to 0.9 for ice and snow, with a corresponding change in the radiation budget. At the same time, latent and sensible heat fluxes from the ocean to the atmosphere are substantially reduced by the insulating effect of the ice and snow cover. The ice insulates water at its freezing point from the air, which is commonly some 30°C below zero, except in the leads and over thin ice, where the air contacts the water and causes large turbulent fluxes (Maykut, 1982). Thus, the surface heat flux is determined by the amount of open water and thin ice. Also, because the ice surface is radiatively and sensibly cold, stratus clouds form above the sea ice in summertime (Herman and Goody, 1976).

The coupling of dynamic and thermodynamic processes, through the response of sea ice to wind and current forcing, the large latent heat of freezing, and the low salinity and thermal conductivity of sea ice, produce the basic polar air/sea climatological mechanisms. One example is sea-surface cooling by ice that melts as it is driven equatorward by winds and currents; another example is the divergence of the ice pack under wind forcing to expose relatively warm ocean water to the cold polar atmosphere. Similarly, an ice cover influences the ocean's mixed layer by altering the surface stress caused by the wind, by changing the stability of the mixed layer through the removal by the wind of fresh water in the form of ice, by driving convection through the production of cold brine by freezing out fresh water, and by releasing fresh surface water during melt. Sea ice also plays a role in the global carbon-dioxide budget by speeding, during freezing, the sinking of carbon dioxide along with other brine components in the surface water, thereby leaving a carbon-dioxide-deficient surface layer after the ice melts (Jones and Coote, 1981).

The material properties of sea ice (its physical and chemical structures) are worthy of study in the absence of specific atmospheric or oceanic processes. For example, the mode of deformational response of sea ice to external stress is quite complex; the large-scale properties of sea ice seem to depend on, as well as control, the geometry of the ridges and leads and the floe fabric of the pack in ways that are not well understood. The material strength of the ice exhibits a strong seasonal cycle, which is long compared to meteorological time scales, but short compared to oceanographic time scales.

Although the greatest impact of ice on the sea is to insulate the water from the cold polar air, the polar oceans remain major regions of heat loss for the World Ocean. While the magnitude of the heat loss from ice-covered seas is not well known, it is a key flux; the value of this loss should be determined because it serves as an important boundary condition for the world's climatic system. The oceans also interact with the ice cover in other ways. Near continental boundaries where the mean winds blow the pack ice away from the coasts, the cold brine resulting from the rapid ice formation continuously sinks, producing cold, dense bottom water.

The brine thus produced over the Eurasian continental shelves is thought to run off the shelves, some mixing with warm Atlantic water and some forming the cold bottom water of the Arctic. Since coastlines are often sites of strong open-water production by shearing deformation in the ice, this process could be a significant heat pathway, but quantitative information is not available. There is also some speculation concerning the role of eddies and upwelling in ice/ocean interactions in both the central pack and at the pack-ice margins where such events have been observed. In general, it is not known if the eddies are driven by an ice-related process, or if they are simply found beneath the ice. The ice-margin upwelling seems to be related more to the different wind stresses acting on the ice-covered water than to the wind stresses acting on the adjacent open water. However, the strength of this action and the physical and biological consequences of upwelling are also not well known.

III. Sea-Ice Science Questions

The major sea-ice science questions to be answered in the Alaskan Arctic SAR program arise from the effect of sea ice in the air/sea/ice system. They deal primarily with the role of sea ice in the disciplines of oceanography, atmospheric circulation, and climatology, but interest in sea ice exists also in biology, geology, and engineering. The major questions are:

(1) What is the seasonal cycle of the rheology of the various pack-ice zones?

(2) What are the heat, mass, and property fluxes within the different sea-ice zones, and how do they influence oceanic and atmospheric circulation?

(3) What are the characteristics of ice production, deformation, advection, and decay in the pack-ice zones?

(4) What are the origins of transient oceanic features of the ice-covered oceans, and how does the ice field interact with them?

These questions will be dealt with in more detail in their regional contexts to illustrate the nature of the problems, the role of SAR data in attacking the problems, and the auxiliary data needed to produce the full complement of information. For the Alaskan receiving station under review, the regional sea-ice zones are the central gyre of the Beaufort Sea, the shear zones of the Beaufort and Chukchi Seas, the Bering Sea, the bays and sounds of the Alaskan and Russian Coasts, and the whole Arctic basin.

IV. SAR and Sea Ice

To make estimates of the strengths of air/sea/ice interactions through studies of sea ice, information on a number of ice characteristics is needed. Table 1 lists these characteristics and the applicability of SAR to their study. Of the list in Table 1, SAR provides detailed quantitative information on four items and qualitative information on another three items. These applications have been amply demonstrated by analysis of Seasat SAR images of the ice in the Beaufort and Chukchi Seas and in the waters of the Canadian Archipelago. These images have been analyzed for ice coverage, fast-ice breakup, ice velocity, ice deformation, and floe decay. Most significantly, there is now no question that ice floes can be tracked with great precision (Hall and Rothrock, 1981), providing a detailed specification of the ice velocity and deformation field (Figures 2 and 3). In addition, the complex structures of the ice edge (Figures 2 and 6), of lead patterns (Figure 7), and of zones of deformed ice (Figure 8), are clearly displayed as are the presence of hazards such as ice islands and large floebergs (Figure 9).

However, the brief lifespan of Seasat provided data over ice in the Arctic region only during the summer and early fall, when little or no ice was present in the Chukchi Sea, Bering Strait, and Bering Sea. Further, Seasat failed before the sched-

Table 1. Sea-ice characteristics and SAR applicability

Characteristic	SAR data
Extent	Good
Movement and deformation	Good
Snow cover	Not known
Ice thickness	Some
Internal geometry (floe sizes, lead patterns)	Good
Surface roughness	Good
Ice types	Some
Physical properties (such as temperature, salinity, and strength)	Some

uled complementary in situ ice observations could be made. There was also no opportunity to make detailed observations on the winds, currents, and temperatures that drive the air/sea/ice interactions. Even so, the utility of SAR in studying ice dynamics was proven (Hall and Rothrock, 1981, and Leberl et al., 1983), and the impact of the Seasat SAR imagery on the ice community has been sufficiently large to allow recommendation of SAR as the prime ice sensor in the NASA ICEX report (Ice and Climate Science Working Group, 1980); it was proposed for a similar role in the joint Canadian/United States RADARSAT program (Carsey et al., 1982).

Figure 6. Seasat SAR image taken of the Chukchi Sea marginal ice zone;
Rev. 1482, October 8, 1978.

0   2 km
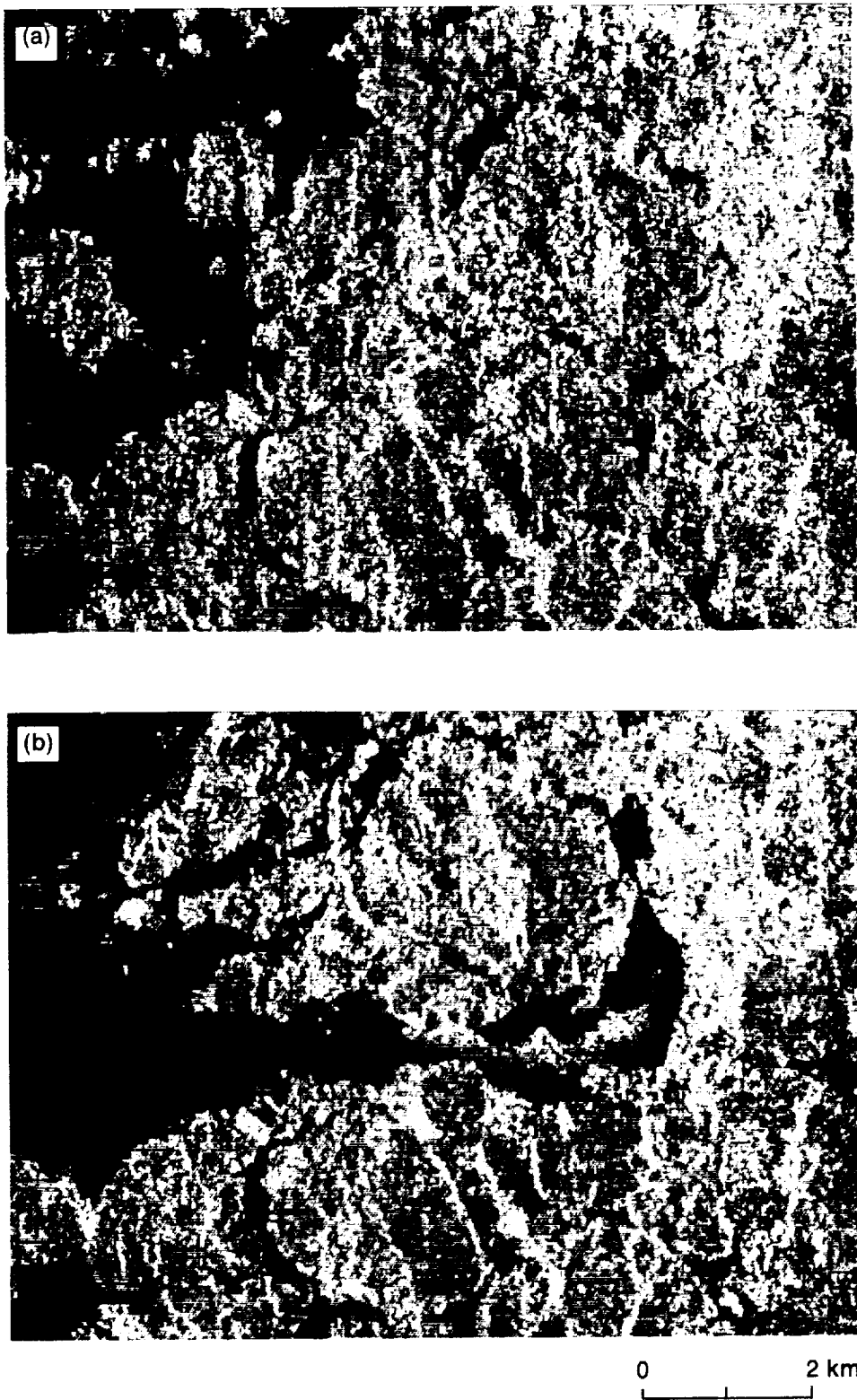
Figure 7. Enlargement of a pair of Seasat SAR images in the marginal ice zone in the Beaufort Sea off Banks Island: (a) Rev. 1382, October 1, 1978; (b) Rev. 1425, October 4, 1978.

15

N

0   10 km
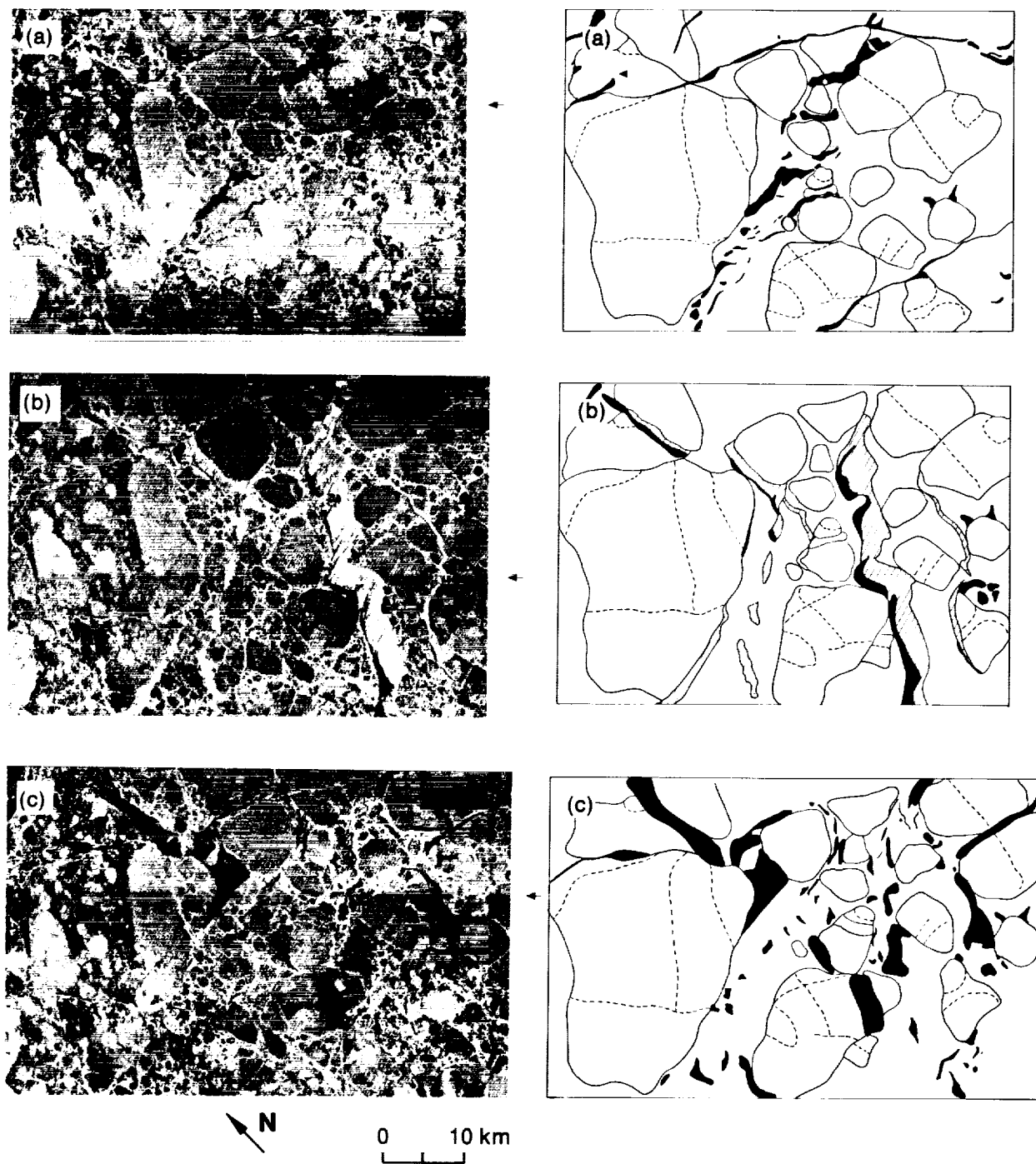
Figure 8. Enlargements of three Seasat images taken over a 6-day period in Melville Sound, Canada. The corresponding sketch maps indicate major floes (solid lines) with some distinguishing features (dashed lines), leads and/or new ice (dark zones), and grease ice "tadpoles" (stripped zones). Arrows indicate adjoining swaths: (a) Rev. 1365, September 30, 1978; (b) Rev. 1408, October 3, 1978; (c) Rev. 1451, October 6, 1978.
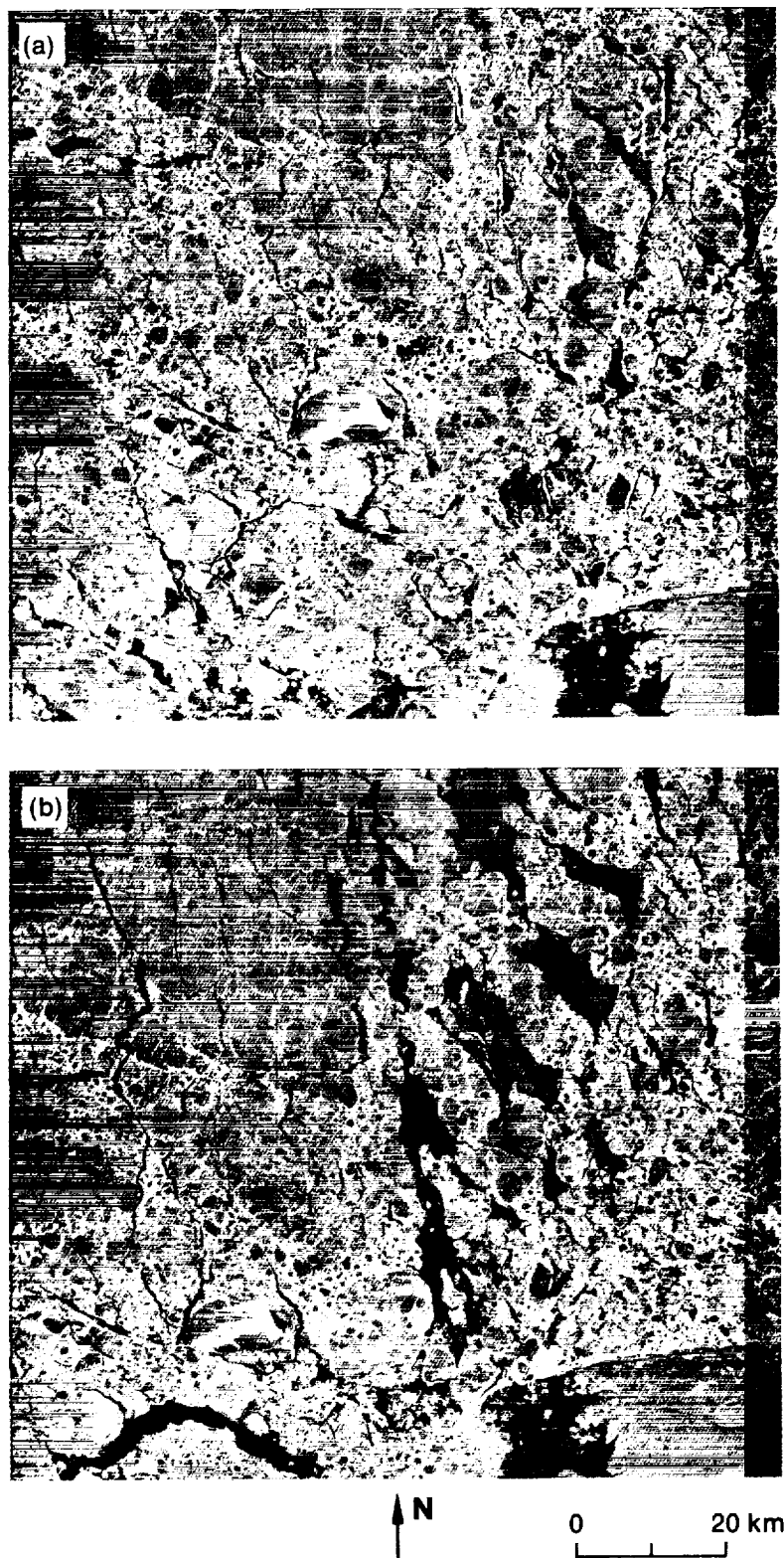
Figure 9. A pair of Seasat SAR images taken off Banks Island (lower right) with a large, centrally located ice island (called "T-3"): (a) Rev. 1409, October-3, 1978; (b) Rev. 1452, October 6, 1978.

V. Sea-Ice Research Opportunities Near Alaska

Several geographic zones of sea ice with high scientific and operational interest would be covered by a SAR receiving station located in Alaska (Table 2). Projected coverage for a 3-day period is shown in Figure 5. Each zone has a particular set of associated opportunities for science as described in this section.

A. Beaufort Sea Gyre

The Beaufort Sea, that portion of the Arctic Ocean north of eastern Alaska and far western Canada, is principally a vast expanse of ridged and hummocked old ice turning slowly clockwise in a wind-driven gyre some 1000 km across. This large-scale feature, located under a quasi-stationary, atmospheric anticyclone, has been the subject of numerous earlier investigations, including the largest sea-ice study, the Arctic Ice Dynamics Joint Experiment (AIDJEX; Untersteiner, 1980). This is an interesting region for studying the response of sea ice to large-scale, presumably relatively smooth and simple wind and current systems. It should be noted, however, that storm-passage events that reverse the motion of the gyre have been observed. Nevertheless, detailed case histories of both the rule and the exceptions, and attempts to model their motions, are few.

The primary science interest lies in improving the understanding of, and the ability to forecast, the response of the sea ice of the central Arctic pack to atmospheric and oceanic forcing. Largely as the result of interactions within the pack itself, this is very complicated. These interactions include the formation of leads and pressure ridges, ice growth and decay, the lateral transfer of stress within the ice and the dependence of internal stress on the nature of the gross ice fabric and ice thickness distribution, seasonal changes in the top and bottom roughness of the ice, and variations in the internal ice properties. The SAR images of central pack ice shown in Figure 3 illustrate several ice features, including pressure ridges, leads, and floe size and geometry, which are useful in identifying specific floes that can

Table 2. Sea-Ice research opportunities in the Alaskan region

Geographical areas	Ice type(s) present	Broad scientific research opportunities	Past and/or present major programs
Beaufort Sea gyre	Annual and multiyear ice, including pressure ridges, leads, and ice islands	Response of sea ice to large-scale geophysical driving mechanisms (dynamic and thermo-dynamic)	AIDJEX/drifting ice stations (Arctic Research Laboratory Ice Station (ARLIS), T-3)
Beaufort and Chukchi Sea continental shelves	Annual and multiyear ice, including heavy pressure ridges, leads, polynyas, and ice island fragments	Geophysics of ice/shore/ shelf interactions, including fluxes in the flaw lead, shear-ridge formation, gouging, and ice override of the shore; practical problems of ice hazards posed to offshore petroleum exploitation.	OCSEAP/petroleum-industry research
Bering Strait	Annual and some multiyear ice	Ice flow and breakout through a narrow strait	BESEX (U.S.-U.S.S.R.), PROBES, NOAA PMEL studies
Bering Sea ice margin and shelf	Annual ice	Ocean/ice/atmosphere interactions at the ice edge (effects of the ocean and atmosphere on the location of the edge and vice-versa); severe storms	MIZEX (West), ASI80s
Entire region	All ice types	Effects of sea ice on climatic change; ice forecasting.	Global climatic model simulations

then be monitored over time for drift and morphological change to provide valuable data for studying air/sea/ice interactions. The relative velocity vectors resulting from precision analysis of this image pair are shown in Figure 3(c) and indicate the highly complex air/sea/ice interactions that occur in this region.

Although forecast models of varying degrees of complexity exist, including both regional and local ice models that were specifically formulated to describe the Beaufort pack (Hibler, 1981), the data are still largely lacking to validate these models. Such verification, focusing on the Beaufort Sea gyre since it is perhaps the most studied region, is very important because these models are needed to extend the existing, highly limited observational time series in other regions.

B. Beaufort and Chukchi Sea Continental Shelves

On the continental shelves and coastlines of the Beaufort and Chukchi Seas, the edges of the gyre shear with enormous force against the ice held fast at the shore. This mechanical interaction produces large flaw leads, shear ridges, and rubble fields; an example is dramatically shown in a SAR image pair (Figure 9) taken 3 days apart: the southward movement of pack ice along the coast of Banks Island results

in large leads covered with new, smooth ice, while the pack ice on the right portion of the SAR image pair remains compacted against the northern shore. In some cases, side-scan sonar surveys show that ice blocks and pressure ridges dragged across the ocean floor produce deep gouges and rework the sediments. In addition, ice can occasionally override the low-lying barrier islands and the shorelines of these coasts.

Research opportunities in the shear zones are of interest to both engineers and scientists. Engineering interests will be discussed under Offshore Operations, below. The scientific interests concern the heat and mass budgets in both the atmospheric boundary layer and the shelf waters; these budgets are a consequence of the open-water and new-ice production in the flaw lead. Elements of the process not well understood include the results of the production and drainage of cold dense brine in the shelf and slope waters, the nature and extent of the shear deformation in the ice pack, and the annual net ice production in the flaw lead. These issues may have even more significance in the ice-laden seas of the Southern Ocean; what is learned off Alaska might be applied to that far more remote area.

C. Bering Strait

Near the Bering Strait, ice motion is dominated by coastal restrictions. Any wind stress across the sea in this region will produce ice deformation against land, and may force ice through the strait. Observations of this region would provide an opportunity to study the flow of ice between the Arctic Ocean and the Bering Sea. The occasional dramatic ice breakouts have been modeled as extrusion flow. A more realistic model would treat the ice as two-dimensional granular material passing through a constriction (a problem similar to that of grain passing through a hopper). Additionally, movement of both ice and water into and out of the Arctic Ocean through the Bering Strait is important in the Arctic Ocean's circulation and heat balance, although not as important quantitatively as the flow through the Fram Strait to the North Atlantic. Bering Sea water can be identified over vast distances near the Arctic Ocean's pycnocline.

To advance modeling of this phenomenon, information is needed on the general fabric of the ice and its deformation patterns as it passes through the strait (Sodhi, 1977). SAR images would be ideal for such studies as they would allow detailed observations of the formation of ice arches across the strait and between Wrangel Island and shoal areas in the Chukchi Sea. In the past, attempts to study the characteristics and flow rates of ice in this remote region by the use of shore-based radar systems were not successful because of logistical problems and the limited range of the radar.

D. Bering Sea Shelf

Sea ice in the Bering Sea forms principally near the land masses and is blown southward usually to remain north of the shelf break, and thus generally covers only the area of the continental shelf. However, the shelf is very large and seasonal variations in ice extent are quite substantial. The ice is mostly highly mobile annual ice, and will occasionally intrude northward through the Bering Strait. The dynamics and thermodynamics of the sea ice are driven by storms centered to the south of the ice and moving to the east across the Pacific Ocean (Overland and Pease, 1982). The ice movement is nearly meridional, and the local deformation is by rafting, the

smooth sliding of one flat floe over another, which is quite different from the much-studied ridge-building deformation, the piling up of blocks of ice at the floe edge, characteristic of heavier ice found to the north in the Arctic region. Inter-annual variations in ice extent are quite large.

The Bering Sea Experiment (BESEX) focused on airborne passive microwave remote sensing for determining sea and ice characteristics; it was jointly carried out by the United States and Russia in this region in 1973. Also, NOAA and NASA have carried out a number of successful but time-limited, combined ship and aircraft studies in this area during the last few years. Interpretation of the more comprehensive, synoptic-scale, long-term data set that would be produced by a SAR system would be a natural extension of this earlier work, and would allow the testing of a variety of forecast models throughout the season.

One particularly interesting aspect of the Bering Sea shelf is the presence of large polynyas that consistently form off the south coasts of the Seward Peninsula and St. Lawrence Island during the frequent periods of strong northerly winds. These polynyas are areas of intense ice generation and are believed to be additional sites where the cold, saline water similar to the bottom water of the World Ocean is formed. The use of SAR imagery, when coupled with IR imagery and the deployment of a number of moored buoys that would measure currents, salinities, and temperatures, would contribute significantly to our understanding of this important geophysical process. Also of scientific interest are the dynamics of ocean currents and ice in shallow seas where ice motion is retarded by stress on the ocean bottom.

E. Bering Sea-Ice Margin

The southern sea-ice boundary in the Bering Sea is a free-ice margin, unrestricted in its movement and location by any land. Powerful storms sweep up the Asian coast and cross the North Pacific and the Bering Sea, dramatically deforming and advecting the sea ice. These storms then move on into the Gulf of Alaska where they often deepen before migrating across the North American continent along the midlatitudes. It is thought that these cyclonic atmospheric disturbances may be steered by the edge of the ice pack, or more accurately by the reduction in surface heat flux north of the edge, while mean atmospheric and oceanic processes determine the ice-edge location on longer time scales. A first attempt to study the physical processes and interactions between the ocean, the ice, and the atmosphere is underway as part of the Air-Sea-Ice Program (ASI) and its first experiment, the Marginal Ice Zone Experiment (MIZEX), but synoptic, fine resolution, all-weather coverage of ice features and characteristics is not currently possible. The nature of the ice edge is complex, often containing long ice bands oriented across the wind or herded into parallel "tadpoles" by Langmuir-type rolls along the wind, which suggests eddies on a variety of scales, as seen in Figure 6, which shows an ice edge in the Chukchi Sea. The basic scientific questions concern the ice edge: what controls its location, what are the net vertical and horizontal fluxes, how can the ice deformation be characterized, and what are the local and larger-scale dynamic responses of the ocean?

In Figure 6, the ice edge is located in the upper left corner while the dark zones are comprised of new or grease ice, millimeter-scale ice grains floating in a thick viscous layer at the sea surface; this layer effectively dampens the small-scale

surface waves to which SAR is sensitive. The tadpoles are best seen at the boundary of the dark, icy zones and the bright, wind-roughened open water. The curving filaments of grease ice in the lower left of the image indicate the presence of eddy currents near the surface. Lastly, swell can be seen impinging at and even propagating into the ice edge as well as into the areas of the surface eddies. The high-resolution, all-weather capabilities of SAR will be essential in unravelling the physical principles that control such complex phenomena.

F. Entire Arctic Basin

Across the entire Arctic region, extending perhaps to latitudes as far south as the Gulf of St. Lawrence (45°N), there is a large annual cycle of sea-ice retreat and advance changing, summer to winter, from 8- to 15-million km^2 and incorporating some 20- to 30-thousand km^3 of ice, respectively. Locally, the ice cover is not consistent from year to year, but can have differences in edge location of 200 km between two winters or summers; the overall total extent and mass balance, however, have fairly small interannual changes in the present climate.

It is frequently suggested that the total sea-ice extent and mass balance are perhaps globally the most sensitive geophysical indicator of changes in mean annual air temperature. This may be particularly useful in climatic monitoring of the potential effects of carbon-dioxide increases (Manabe and Stouffer, 1980; Parkinson and Kellogg, 1979). However, less obvious indirect relationships may also exist in that changes in temperature due to less or thinner ice may affect the atmospheric baroclinicity, resulting in changes in the heat balance, the tracks of cyclones, and the wind patterns that in turn will, through ice dynamics, affect the location of the ice edge. Also, these dynamical effects brought about by changes in the wind field can alter the oceanic heat budget, ultimately altering, at depth, the heat exchange between the Arctic and the North Atlantic, as well as changing the annual cycle of the locations of oceanic fronts, thus shifting hemispheric weather patterns. These issues are indeed global and call for joint international experiments merging data from all three proposed Arctic SAR receiving stations for ERS-1 (Figure 4). The combined zones of the three stations, located in Kiruna, Sweden; Prince Albert, Saskatchewan, Canada; and Fairbanks, result in coverage of almost the entire region.

The study of the mass balance of sea ice requires hemispheric observations of the ice extent, concentration, thickness (or its proxy ice type), and velocity. Particular attention should be paid to such large-scale ice kinematic features as the transpolar drift and the Beaufort Sea gyre. For studies of the whole Arctic region, particularly in measurements of the ice extent and concentration, the merging of passive microwave data, scheduled to be available from the U.S. Navy Special Sensor Microwave Imager (SSM/I), with SAR data should be valuable and must be evaluated. Ice thickness has not been measured by satellites, but perhaps can be estimated by combining satellite-derived ice-type abundances and the few submarine sonar profiles available. Ice velocities at points in the central Arctic have been measured by air-deployed, satellite-tracked buoys since 1979 (Thorndike and Untersteiner, 1982). The positions of the buoys are monitored many times a day, but the small number of buoys and the large distances between them provide data on only large-scale motions. Also, some critical regions are inaccessible to buoy monitoring. These include the entire Eurasian continental shelf, which is out of range of buoy deployment, and regions close to shore near the free-ice edge where buoys would have an

unacceptably short life expectancy. It is in these regions that SAR, with its proven ability to accurately measure ice drift (Hall and Rothrock, 1981), should be used to extend our information on small-scale motions in the ice velocity field. As seen in Figure 3, where over 750 common features were tracked within a 100- by 100-km area, the density of measurable points can be very high in SAR imagery. The resulting ice motion vectors from Figure 3 are quite variable in velocity and direction and show surprising structure. To evaluate the forcing mechanisms, these vectors can be compared to atmospheric and oceanic conditions and models, and to large-scale motions. A possible outline for such a velocity measurement plan could involve periodic sampling of selected regions around the Arctic, including the northern Alaskan and Siberian coasts, Fram Strait, Bering Strait, and the Greenland and Iceland Seas.

G. Offshore Operations

Numerous practical problems due to sea ice have to be faced by the petroleum industry, which is involved in offshore oil and gas exploration, development, and production on the Beaufort and Chukchi Sea shelves. Similar problems are also faced by the commercial transportation and fishing industries. These industries must design systems that can survive under harsh conditions dominated by the presence of sea ice. Problems range from ice forces acting on ships and offshore structures to estimates of the rates and depths of ice-induced gouging of the sea floor and of wave forces when the effective fetch is limited by the presence of pack ice. In most of these problems, although various average values are of interest, it is the extreme 10-, 20-, or 100-yr values that are most important. To make progress in solving many of these problems, improved "intelligence" on the present state of ice conditions is badly needed. One particularly important problem is our present inability to narrow the gap between geophysical-scale ice/ice interaction forces, which are small and can be estimated from ice-dynamic models, and engineering-scale ice/fixed-structure interaction forces, which are large and presumably a function of the scale of the structure and the granular nature or fabric of the pack. Sequential SAR imagery would be very useful in studying the changes in the "granularity" of the pack with time of year and in providing an observational base for approaching this problem.

These coastal waters carry shipping and drill-ship traffic in the summer and will carry ice-breaking freighters and tankers during the winter when year-round navigation of the Arctic Ocean becomes a reality. Navigation must first be considered on two time and space scales: one related to avoiding areas of generally converging ice whose motion is associated with the passage of weather systems with time and space scales of less than 5 days and several hundred kilometers, and another related to choosing through the pack a line of least resistance, principally leads, which would have scales of a few hours and tens of kilometers. Figure 8 illustrates the local, small-scale problem. The focus of this figure is directed to the same multiyear ice field on all three SAR images, taken over a 6-day period during which rapid ice deformation and formation of leads and new ice (both dark areas and striped areas) is occurring. Also, in the summer, precise information on the ice-edge location is needed as the open-water path can be very narrow, or closed, or rapidly moving. The drift vectors overlain on the SAR image of the marginal ice zone shown in Figure 2 are derived from tracking floes from this image to another image (not shown) taken 3 days later, and they indicate that motions of up to 25 cm/s can occur at the ice edge. Another potential operational problem is that of

deciding when and if to terminate offshore operations when an anchored drill ship or offshore platform is threatened by a collision with heavy ice floes, an ice island, or an iceberg.

It should be noted that although such problems are not scientific in the strict sense, they clearly pose many of the same technical problems science faces in the areas of rapid data processing and information extraction and transmission, as well as ice modeling. The solution of such problems will require insight derived from data on ice characteristics and dynamics. A system of three SAR receiving stations (Figure 4), as discussed in the previous section, would have to include an Alaskan station as a key element for the American Arctic and would present a unique opportunity to study synoptic, large-scale ice dynamics for scientific and operational-problems research over the entire Arctic.

VI. Oceanographic Research Opportunities in Ice-Free Seas and Ice Margins

The Gulf of Alaska and the ice-free portions of the southern Bering Sea are frequently traversed by intense storms. Data on the generation and propagation of surface waves by these storms are needed for improving wave forecasting models and shipping operations in these little-studied but economically valuable regions. SAR imagery has proven particularly useful for providing data on the wavelength, propagation direction, and amplitude (with additional calculations) of surface waves. Figure 10 shows the diffraction of surface waves around Kayak Island; the waves were probably generated by two extratropical cyclones that passed through the Gulf of Alaska 1 to 2 days earlier. Also, internal waves are generated in the warm months along the sharp, seasonal thermocline in the Aleutian Islands region and on the Gulf of Alaska shelf breaks. Internal waves, extensively imaged by the Seasat SAR, could be important in mixing the surface layers in these regions. Recent research (Processes and Resources of the Bering Sea Shelf (PROBES) and Outer Continental Shelf Environmental Assessment Program (OCSEAP), see Table 2) also suggests that synoptic-scale weather affects the biological production of the rich fishery on the southeast part of the Bering Sea shelf through the effect on the physical properties of the water column (Alexander and Niebauer, 1981).

For example, it has been suggested that the survival of pollock larvae is linked to the coincidence of favorable or calm "windows" in the weather. The onset of the spring bloom seems to be associated with the weather calming enough to allow water column stratification to occur. Both of these phenomena have time scales of a few days. Visible and IR satellite observations are a help in observing these conditions, but this region is so often cloud covered that such data are limited. Thus, large-scale coverage of the sea state of the Bering Sea is largely lacking during periods when it is most needed. As the intensity of the SAR return is related to the sea state, SAR imagery would be most useful in such studies.

KAYAK ISLAND - COPPER RIVER, ALASKA
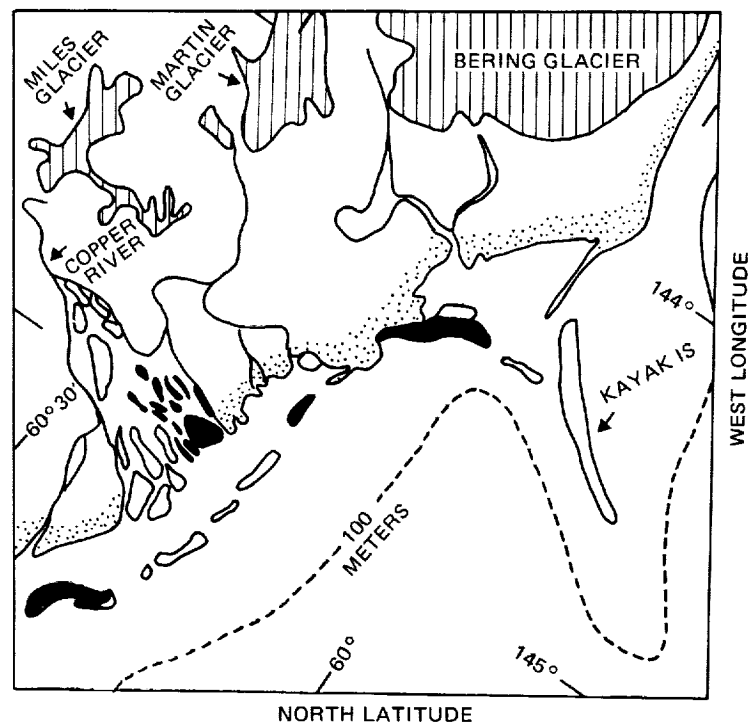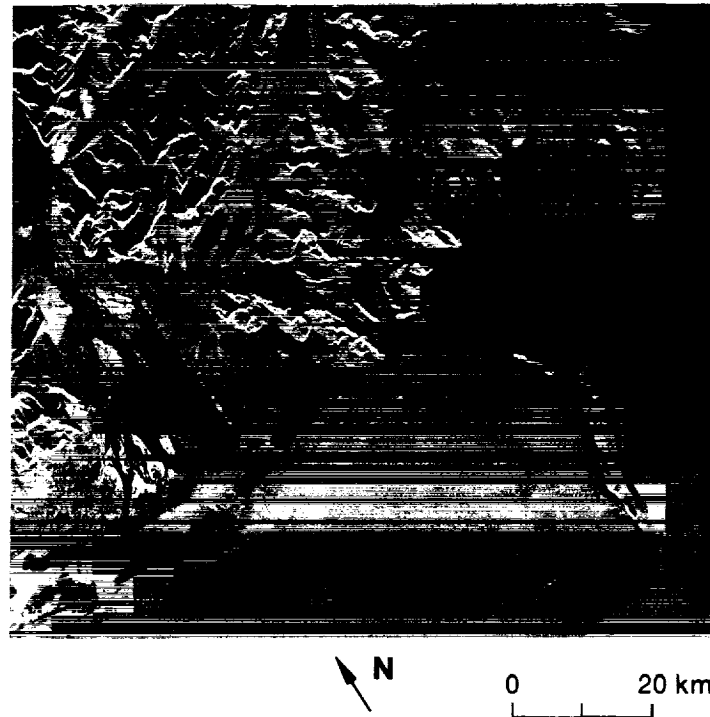

N

0   20 km

NORTH LATITUDE

Figure 10. Surface waves diffracting around Kayak Island in this Seasat
SAR image; Rev. 1126, September 13, 1978.

Other oceanographic phenomena occur along the Bering Sea shelf and seasonally along the ice-free margins of the Beaufort and Chukchi Seas. There are several recorded instances of eddies and fronts beneath the central pack as well as at the ice margins, where upwelling events have also been observed. Additionally, eddies 100 to 200 km in diameter have been observed along the shelf break of the Bering Sea. The physical role of these features, the mechanisms that generate them, and their interaction with the ice are largely unknown. Although these particular features are perhaps better observed with IR satellite imagery, similar features have been detected in Seasat SAR imagery because of the modulation of small-scale surface waves by currents and temperature boundaries associated with these features. The persistent cloud cover of the Arctic region greatly limits the number of IR observations, enhancing the value of SAR for eddy and front detection. For example, the surface features seen in Figure 11 are small cyclonic eddies closely associated with sharp fronts at the ice edge. Lastly, surface waves are known to break up floes at the ice margins and this process could be studied in SAR imagery, as seen previously in Figure 6.

N

0   10 km

Figure 11. Seasat SAR image of small eddies associated with sharp temperature fronts at an ice margin (right) in the Beaufort Sea; Rev. 351, July 21, 1978.

VII. Alaskan Research Opportunities in Geology, Glaciology, and Botany

Terrain mapping and studies of terrain modifications are difficult in Alaska, where much of the surface area is primarily cloudy and poorly accessible. Numerous on-going geologic mapping and mineral exploration and assessment programs are currently underway in Alaska. SAR imagery would provide valuable data sets for scientific research in these areas. A particularly interesting situation exists for geologic SAR studies in Alaska because extensive radar images of this region were acquired by Seasat, and the opportunity to reexamine some sites after a 10-yr interval would provide an excellent data base to study changes on that time scale in areas such as river deltas, shallow-water bathymetry, coastlines, and river valleys.

Requirements for the proposed SAR coverage would vary according to the specific area of interest and the exact application. In some cases, time dependence and repetitive coverage are essential; in others they are of little significance. Following are some examples.

The Alaska Peninsula and Bristol Bay (approximately between 54 to 60°N and 152 to 164°W) are consistently cloud-covered areas with petroleum and geochemical development potential. SAR images would be valuable in geologic mapping of the area and in monitoring changes in the near-shore bathymetry of the Bay.

The glaciers of the Malaspina and Wrangell Mountains occupy the area between approximately 60 to 62°N and 138 to 150°W. These are massive mountain glaciers, many of which have extensive histories of sudden rapid movements called surges. This region also includes the most heavily populated portion of Alaska — around Anchorage. The Malaspina Glacier, shown in Figure 12, is fed by several smaller glaciers, whose interaction produces the distinctive flow patterns. SAR images would be useful in monitoring the movements of glaciers in this region.
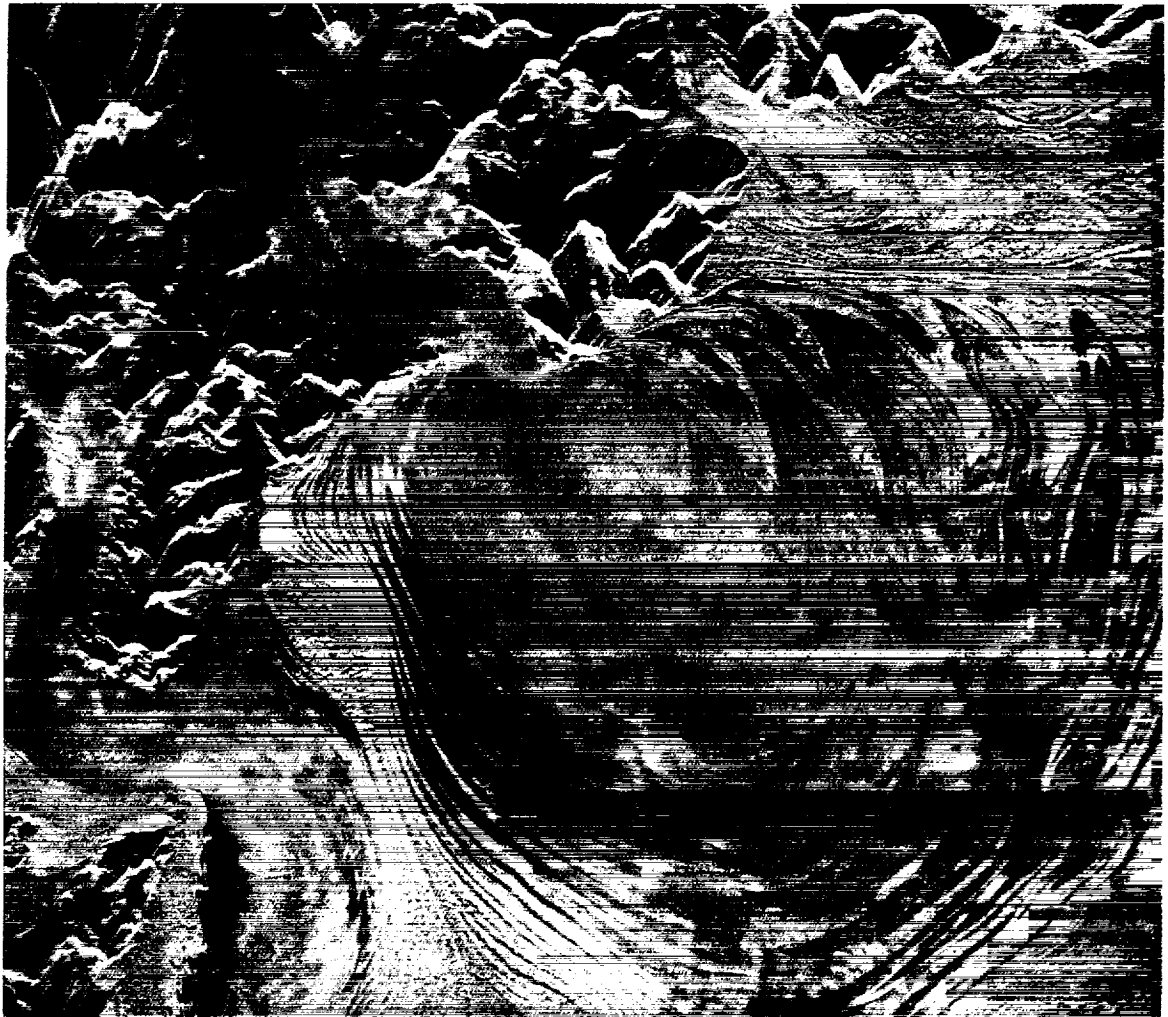
N 0 10 km

Figure 12. Seasat SAR image of a large piedmont glacier near the southern coast of Alaska; Rev. 552, August 4, 1978.

In the Yukon River valley and upland (approximately between 62 to 65°N and 144 to 164°W) several geomorphic processes are believed to be associated with the annual breakup of the ice cover of the Yukon River. Little is quantitatively known about these processes. In this area of Alaska, SAR coverage at selected seasons would provide a significant new data base for fluvial geomorphologists. Additionally, it would provide glaciologists with important observations on glacial movements and surges in the adjacent Alaska Range. Figure 13 shows a portion of the Alaska Range around Mt. McKinley (which is difficult to discern because of the severe layover resulting from the steep incidence angle of the Seasat SAR) and includes examples of a surging or pulsing glacier (Tokositna) distinguished by wavy moraines, and a glacier (Ruth) that moves at a more constant rate.

On the coastlines of Alaska, numerous river deltas are known to change inter-annually; the shallow-water bathymetry of the adjacent seas is also thought to be highly variable. Both of these phenomena can be studied by the proposed SAR imagery, although the relationship of surface current flow to the bottom features — the relationship that causes the signature detectable by SAR — is still not well understood. The Frontispiece is an image of the Kuskokwim River, where deep channels separated by extensive shallow sand bars (dark areas) produce variations in the river surface flow. Acquisition of a new SAR data set after the 10-yr gap since Seasat images were acquired would mean that the 10-yr time scale as well as the interannual time scale could be studied.

The U.S. Geological Survey has an extensive mapping project in Alaska, the Alaska Mineral Resources Assessment Project (AMRAP), directed at assessing the mineral resources of the state. Work is in progress in portions of about 15 different map areas (at scales of 1:250,000), only a small part of the more than 140 map areas that cover the State of Alaska. Selected SAR coverage of areas that are in the process of being studied would be helpful for geologic mapping. In addition, the surface observations of AMRAP could contribute to research into the physics of radar remote sensing.

Large-scale studies involving the vegetation in Alaska are further possible applications of SAR imagery. The North Slope, seen clearly in Figure 14, is charac-terized by extensive lakes and wetland vegetation in the coastal zone, tussock tundra in the foothills, and rocky outcrops and mat vegetation in the Brooks Range. Map-ping of these different plant/permafrost zones has been undertaken using Landsat data. However, the sensitivity of SAR to variations in soil moisture and surface roughness, in this case due to different types of plants and their effects on soil structure, could provide additional useful information on environmental changes. Specifically, the freeze/thaw cycles of these vegetative zones could be monitored as well as the related hydrological questions of ground-water drainage, the extent and thickness of lake ice, and the breakup of ice in streams. The ecological and environ-mental relationships of tundra and permafrost are valuable parameters for land use planning and monitoring in this economically valuable region. Also, forestry surveys could be taken in other areas of Alaska, and would include the effects of timbering, disease, and fires on total areal extent.
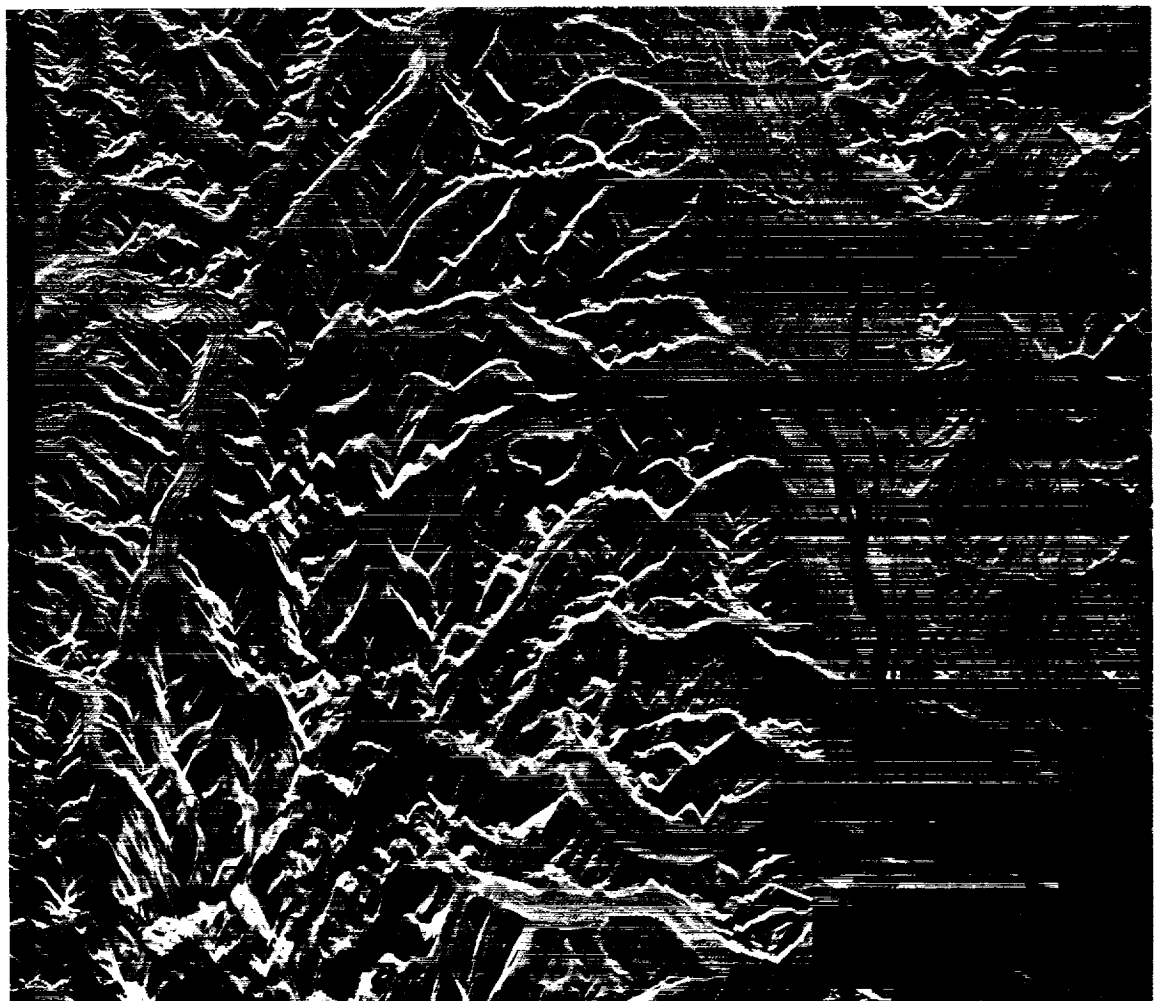
Figure 13. Seasat SAR image with Mt. McKinley (lower left), Tokositna Glacier (central bottom), and Ruth Glacier (just above Tokositna Glacier); Rev. 380, July 23, 1978.
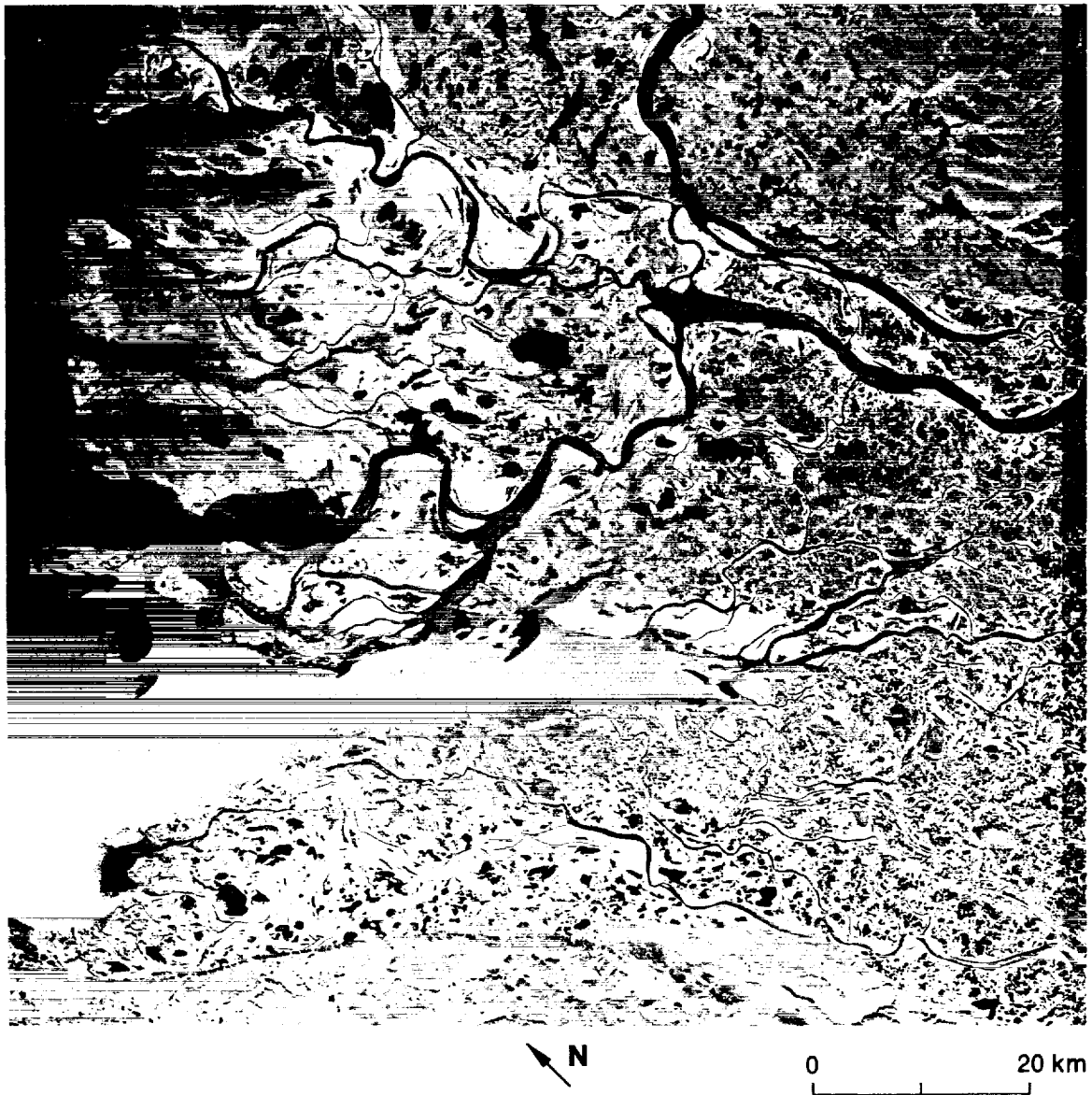
Figure 14. Seasat SAR image of the Mackenzie Delta showing the thermokarst terrain, ponds, and tributaries; Rev. 221, July 12, 1978.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

VIII. SAR in Support of Geoscience

As discussed in the previous sections on research investigations, SAR imagery can be useful for studies of the ice and open water regimes of the ocean environment as well as a wide variety of basic and applied studies relating to the geology, glaciology, and vegetation of the Alaskan mainland. To support these investigations, the best location for the receiving station must be determined and the means of digitally processing the SAR data after reception must be considered.

The Alaskan receiving station should be located to optimize the areal coverage of all the regions of research interest, and satisfy the necessary cost and logistical considerations. The recommended site is near Fairbanks (Figures 4 and 5). A station located farther north, for example at Barrow or Deadhorse, would enhance the ice data set by extending the coverage northward, but would sacrifice oceanographic data from the Gulf of Alaska and raise logistical problems.

The majority of the geoscientific studies described in the previous sections would not require SAR data processed on a real-time basis. Forecast modeling and studies of air/sea/ice interaction, for instance, have not reached levels of sophistication and knowledge that require a rapid turnaround of SAR data or other data sources on an hourly or even daily basis. The SAR data acquired at an Alaskan receiving station could be processed in a slower time frame with acceptable rates on the order of 1 to 2 mo from date of reception to delivery to an investigator. A large backlog of unprocessed data would not be acceptable from several viewpoints and could hamper some studies. However, a few studies would best be served by a rapid turnaround of SAR data. For example, efficient research ship and aircraft routing for any field experiment, either on ice or land, could greatly benefit from having SAR imagery available on an hourly or daily basis. Additionally, opportunistic monitoring of cataclysmic events such as volcanic eruptions, floods, and oil

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spills would be of great scientific value. The capability of having real-time processing of SAR data, even on a limited basis, would be vital support for in situ geoscientific studies.

After the SAR data have been processed into earth-located and rectified imagery, additional processing algorithms must be applied to produce a geophysically useful data product. These algorithms would be principally for the automatic extraction of ice types. Geophysical maps of SAR-derived ice types would be extremely valuable for modeling efforts as well as ice-motion studies and operational activities. However, there has been little effort in developing the necessary algorithms and techniques needed to produce SAR image maps of this kind. Research levels in this area should be increased so techniques will be available at the time of the ERS-1 launch.

IX. Requirements

A. General

To implement these recommendations, NASA will be required to:

(1) Establish a SAR receiving station at a suitable Alaskan location, and implement data processing systems to reduce to images about 9 min of data per day. The rate should preclude any backlog and include a limited real-time capability of about 1 min of data per day (see Appendix B).

(2) Enter into negotiations with both the European Space Agency and the Japanese Space Agency to arrange for daily reception at an Alaskan station of about 9 min of SAR data from ERS-1 and additional data from the Japanese radar satellite. (Characteristics of the ERS-1, Japanese SAR, RADARSAT, and associated satellite systems, as they are now known, are given in Appendix A.)

(3) Continue to cooperate with Canada in developing the RADARSAT Program and at the very least continue the valuable joint field programs and maintain negotiations to assure that it will be possible to receive data from RADARSAT's SAR system.

(4) Increase the level of research in automatic extraction of ice types and, ultimately, ice-velocity information from SAR images, and provide, as part of the Alaskan SAR Receiving Station Program, image processing facilities accessible to the sea-ice scientific community for these purposes.

Meeting these four requirements would accomplish the following:

(1) Provide SAR coverage of the Beaufort, Chukchi, Bering, and East Siberian Seas as well as the Arctic Ocean to the vicinity of the North Pole (80°N latitude) (Figure 5). When these areas of U.S. interest are combined with the imagery available from the receiving station at Prince Albert, Canada, and the station at Kiruna, Sweden, a valuable picture of the ice dynamics of the Northern Hemisphere will result (Figure 4).

(2) Provide greatly expanded SAR coverage of the ice-free areas in the southern Bering Sea and in the northern Pacific. This latter region is a particularly important area in the generation of intense cyclonic storms.

(3) Stimulate the use of SAR imagery in a wide variety of research and operational problems concerning sea ice.

(4) Advance the present capability to interpret SAR imagery from both ice-covered and ice-free oceans by improving our understanding of the factors influencing the radar backscatter coefficient for natural surfaces in the polar regions.

(5) Speed the development of methods for the rapid extraction of quantitative data from SAR imagery.

(6) Provide NASA engineers with additional experience with the data processing problems associated with a spacecraft-borne SAR system (such problems caused difficulties and delays during the Seasat mission).

(7) Provide NASA Headquarters with a broad base of experience that would assist in evaluating the desirability of future participation in proposed SAR missions.

(8) Accomplish all of the above at a small fraction of the cost of developing and deploying a NASA-funded satellite containing similar systems.

B. Specific

The requirements for the Alaskan receiving station are:

(1) The station should be capable of processing a maximum of 3800 image-km of SAR data per day (9 min of instrument time per day). Although the need for the data is basically retrospective (a 1-mo processing delay could be tolerated), processing should occur at a rate equaling the daily acquisition rate so that a large data backlog will not occur.

(2) A small amount of data (1 min/day) would be needed on a rapid (6-h or less) turnaround basis to support in situ ice-research or other field experiments and other opportunistic studies such as oil spills, forest fires, and volcanic activity where time is critical. It may prove adequate to process this imagery in a degraded form.

(3) The station should also have the capability of receiving the radar altimeter and the wave and wind mode AMI data from ERS–1 (see Appendix A) as well as similar, associated data from other satellites. Such subsidiary data would provide valuable quantitative information on the surface roughness of the sea ice and on the winds and waves near the ice edge.

It is recognized that in most cases there will not be a great deal of flexibility possible in the proposed SAR satellite programs of other nations. However, if it is possible to modify their designs and plans, a SAR system for optimum utility should have the following capabilities:

(1) Spatial resolution: based on the results of Seasat, 30 X 30 m is known to give a very useful image containing a large amount of important detail. At the present time, 100 X 100 m would appear to give an adequate image for "quick-look" purposes. However, more experience is needed to establish the optimum quick-look resolution (the shortest processing time possible that still retains the critical elements in the image necessary to deal with sea-ice research).

(2) Swath: although a 75-km swath would be useable, a 200-km swath would be ideal in support of ice-motion studies (i.e., the swath width should be increased as much as possible).

(3) Incidence angle: incidence angles in the 20- to 50-deg range are satisfactory.

(4) Polarization: like polarization (HH or VV) is desirable.

(5) Frequency: the amount of ice data available at 5.3 GHz (C-band) is very limited; however, in the RADARSAT study, it was concluded that 11 to 15 GHz offers the best discrimination between first-year and multiyear ice. If frequencies between 1 and 10 GHz are used, it is recommended that the SAR be supplemented by either a 19- or 37–GHz radiometer or a 11– to 15–GHz scatterometer to allow ice-type discrimination.

(6) Radiometric resolution: a ±1-dB calibration is satisfactory.

(7) Orbits should allow SAR coverage to at least 75°N and preferably 80°N. In addition, there should be a 3-day (or less) repeat cycle on the coverage with some 1-day interval data near the top of the orbit.

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Acknowledgments

Appendix A
Summary of the Systems Scheduled for Launch on ERS-1, the Japanese Radar Satellite, and RADARSAT

A. ERS-1

The instrumentation currently planned for the ERS-1 satellite is described below.

1. Active Microwave Instrument (AMI)

The AMI will be a C-band (5.3-GHz) instrument designed to function in three different modes:

(1) Imaging mode (SAR):

    spatial resolution, 30 X 30 m or 100 X 100 m
    swath width, 75 km
    incidence angle, 35 deg
    polarization, HH
    data rate, 100 Mbits/s

(2) Wave mode (wave scatterometer):

    spatial samples of 5 km^2 every 100 km along track
    incidence angle, 35 deg, side-looking
    polarization, HH
    data rate, 300 kbits/s in bursts

(3) Wind mode (wind scatterometer):

    spatial resolution, 50-km squares
    swath width, 400 km, one-sided
    polarization, VV
    data rate, 1 kbit/s
    wind speed range, 4 to 24 m/s
    wind direction accuracy, < 20 deg

2. Radar Altimeter (RA)

The specifications for this instrument are as follow:

    frequency, 13.5 GHz
    data rate, 10 kbits/s
    altitude measurement, < 10 cm
    wave height, 1 m to 20 m (± 0.5 m)

3. High Accuracy Satellite Position (HASP) Package

The system provides improved positioning that would enhance the usefulness of the data in studies of both oceanography and ice.

The proposed orbit is sun-synchronous and quasi-polar with an altitude range of 750 to 800 km. Therefore, data can be collected on high-altitude, ice-covered areas. It should be noted also that the wave and wind modes of the AMI do not "work" when the instrument is over ice, and that the data rate of the SAR mode is so high that data acquisition is possible only at stations within line of sight of the satellite. Figure 5 shows the projected maximum extent for 3-day coverage of the SAR system proposed for ERS-1 at the assumed geographical receiving range for Fairbanks, Alaska.

B. National Space Development Agency (NASDA) of Japan Radar Satellite

Very little is known presently about this satellite except that the SAR system is believed to be similar to the system NASA deployed on Seasat (L–band, 100-km swath width, 25– X 25-m surface resolution, and HH polarization). The proposed date of launch is presently understood to be after 1988.

C. Canadian/United States RADARSAT Program

The main system is SAR. The proposed characteristics of the system are as follows:

    frequency, C-band
    spatial resolution, 25 X 25 m
    swath width, 200 km
    incidence angle, 25 and 45 deg
    polarization, HH
    revisit interval, daily

Possible secondary sensors are a visible and infrared optical scanner, a passive microwave radiometer, and a scatterometer.

Appendix B
Summary of Radar Data Requirements
for Experiments

A. Sea-Ice Studies

Because of its high albedo and latent heat, and its low thermal conductivity, sea ice has a major influence on the dynamics of both ocean and atmosphere. To understand this influence and to predict its effects, it is necessary to measure these ice characteristics: extent and concentration; movement and deformation; ice types (young or old); floe sizes, lead patterns, and pressure-ridge distribution; ice thickness and snow cover. SAR provides detailed measurements on all these characteristics except ice thickness and snow cover.

The feasibility of detailed measurements of sea-ice motion has been demonstrated using Seasat data. Such measurements would be the first priority of the sea-ice experiments proposed for the ERS-1 SAR (see Table B-1). Specific problems include: improved description of sea-ice mechanics for model development and

Table B-1. ERS-1 SAR operating time: sea-ice studies

Experiment	Location	Images required[a]	SAR Operating time,[b] s/day
Beaufort Sea gyre kinematics	74 to 78°N 130 to 180°W	Two daily intersections of 100 × 80 km; three 500- × 80-km segments every 3 days	60 75
Beaufort-Chukchi continental shelves	69 to 71°N 120 to 170°W 70 to 80°N 120 to 130°W	Two daily intersections of 100 to 80 km; one 500- × 80-km segment every 3 days	60 25
Bering Strait mechanical effects	66°N 170°W	One daily intersection of 100 × 80 km; December to May	15
Bering Sea ice production	56 to 63°N 165 to 180°W	Five 700- × 80-km segments every 3 days; December to April	70
Arctic ice distribution	N of 55°	Above plus data from European sector	
			Total 305

[a]An *intersection* refers to a pair of images taken while the spacecraft has different headings over same site; a *segment* will repeat an essentially identical ground track every 3 days. A *snapshot* is a single image of about 100 × 80 km.
[b]Operating time is averaged over a full year.

forecasting; investigation of sea-ice behavior over the continental shelves; examination of processes involved in the aging of sea ice; detailed observations of ice deformation to improve assessment of sea-ice formation rates and the associated ocean/atmosphere heat budget. Most of this work will be focused on local geographic areas, but we also envisage whole-Arctic investigations of ice extent, motion, and heat budget. These would be cooperative efforts between European, Canadian, and United States scientists, and they would require coordinated data acquisition at all SAR receiving stations.

B. Ocean Studies

SAR measures the surface characteristics of the ocean and detects subtle changes that can be proxy indicators of activity beneath the surface. Under certain circumstances, SAR may be able to give quantitative information on surface waves, internal waves, surface currents, eddies, estuarine flows, ocean upwelling, and shallow-water bathymetry. We have identified three areas of investigation: eddy dynamics and surface waves in the Gulf of Alaska, internal waves and fronts and eddies at shelf breaks, and surface waves, fronts, and eddies in the marginal ice zones. The operating requirements for ERS-1 ocean studies are given in Table B-2.

C. Terrestrial Studies

SAR imagery accentuates the relief of surface topography, and delineates surfaces with different scattering properties. This information is useful in geological mapping, geomorphology, glacial flow, and glacier inventory. Most of the data listed in Table B-3, which lists the operating requirements for ERS-1 terrestrial studies, will be used for geological reconnaissance mapping of Alaska. Images of the same area from two different azimuth directions will be used to compile a mosaic covering much of Alaska once every season. In addition, we have included images required for a periodic glacier inventory, detailed geomorphology, and river-delta and tundra studies. The final entry is for one image per day to cover miscellaneous requirements, such as those associated with oil spills, floods, volcanic activity, fires, and the like.

The total request is for an average daily SAR operating time of approximately 9 min. Although actual requested instrument time will vary from day to day, it is anticipated that peak requirements for an individual experiment will generally be offset by lower requirements for others. We expect winter data requests to exceed those in summer, but the average daily request of approximately 9 min is unlikely to be exceeded by more than a third.

Table B-2. ERS-1 SAR operating time: ocean studies

Experiment	Location	Images required	SAR operating time,[a] s/day
Gulf of Alaska Eddy dynamics	53 to 60°N 130 to 150°W	Mosaics of eddies every 10 days	45
Surface waves		Snapshots to monitor selected storms	15
Bering/Alaska shelf breaks Internal waves Eddies, fronts	50 to 60°N 160°W to 166°E 53 to 60°N 130 to 150°W	Snapshots to monitor selected locations	40
Marginal ice zones Eddies, fronts Surface waves	Beaufort, Chukchi, and Bering Seas	Snapshots to monitor selected locations	20
			Total 120

[a]Operating time is averaged over a full year.

Table B-3. ERS-1 SAR operating time: terrestrial studies

Experiment	Location	Images required	SAR operating time,[a] s/day
Alaska Peninsula geology	54 to 60°N 152 to 164°W	Mosaic images once per season, two azimuths	60
Glacier inventory	60 to 62°N 138 to 162°W	Mosaic images once per month	15
Yukon River geomorphology	62 to 67°N 144 to 164°W	Mosaic images once per season, two azimuths	20
River deltas; bathymetry; North Slope pond evolution	Near coast	Snapshots, annual repetition	15
Tundra freeze-thaw cycle	On North Slope	Five snapshots taken weekly, June through September	5
Targets of opportunity (e.g., oil spills, floods, forest fires, geological field studies, volcanic activities)	Alaska and coastal waters	As needed, but not to exceed one snapshot/day	15
			Total 130

[a]Operating time is averaged over a full year.